Photonic Communications and Information Encoding in Biological Systems

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Abstract

The structure of optical radiation emitted by the samples of loach fish eggs is studied. It was found earlier that such radiation perform the communications between distant samples, which result in the synchronization of their development. The photon radiation in form of short quasi-periodic bursts was observed for fish and frog eggs, hence the communication mechanism can be similar to the exchange of binary encoded data in the computer nets via the noisy channels. The data analysis of fish egg radiation demonstrates that in this case the information encoding is similar to the digit to time analogue algorithm.

1 Introduction

Currently, the term 'biophotons' is attributed to the optical and UV photons emitted by the living bio-systems in the processes which are different from standard chemi-luminescence. Their systematic measurements by the low-noise electronic photo-detectors was started about 1978 [1, 2]; the biophoton production (BP) in optical and close UV range was established now for large amount of bio-systems [3, 4]. It was found that its rate and other parameters are quite sensitive to the characteristics of bio-system and its development. Because of it, the biophoton measurements are applied now in many different fields from medical diagnostics to agriculture and ecology [2].

The energy spectrum of biophotons is nearly constant within optical and soft UV range practically for all studied bio-systems, so it essentially differs from the spectra expected for the system with the temperature about 300^0 K, which in this range should fall on 15 orders of magnitude [2, 3]. The detailed BP mechanism is still unknown, but such excitations can be stipulated by the biochemical reactions, in which oxygen atoms are bound to the proteins and acids [2, 3]. The typical bio-photon rates are quite low, however, the multiple

experiments evidence that such radiation can perform the effective signaling between distant bio-systems. In particular, being radiated by the growing organism or plant and absorbed by the similar one at the distance about several cm, it can rise the rate of cell division (mitosis) in it up to 30% relative to the standard values. This phenomenon called mitogenetic effect (ME) is extensively studied in the last years [2, 3]. Note that the artificial constant illumination by the visible light, even 10^4 times more intense, can't induce the comparable gain. The communications of some other types were reported also; for the bio-systems in the state of abrupt stress or slow destruction (apoptosis) such radiation can change the state of other bio-systems in the similar depressive way [2, 5].

Until now, ME and other biophoton properties can't be described within the standard framework of cellular biology. In our previous paper the model of information exchange between the bio-systems by means of optical radiation was proposed [6]. We've assumed that the main features of such communications can be similar to the information exchange between the distant computers by the binary encoded messages. This hypothesis is prompted by the experiments which show that the radiation of some species consists of narrow quasi-periodic bursts (fig. 1), so its time structure is similar to the sequence of electronic or photonic pulses which transfer information in the computer communication channels [1, 4]. To check our model in more detail we performed the data analysis for the radiation from loach fish eggs measured by the photomultipliers [1, 3]. Here some our results on the radiation structure are described, in particular, the possible algorithm of photon signal encoding in the fish egg communications is obtained.

2 Model of Bio-System Communications

Before considering the photon exchange between the distant bio-systems, it's worth to discuss how such communications can be released inside the same dense bio-system. The optical and UV excitations in the dense media exist as the quasi-particles called excitons which can spread freely through the whole media volume [7]. They are strongly coupled with electromagnetic field, so they can be effectively produced during the photon absorption by the media, the inverse process results in the photons emission from the system volume. It's established experimentally now that the excitons play the important role in the energy transfer inside the bio-systems, in particular, during the photosynthesis in plants and bacteria [9, 8]. Photon production related to the nonlinear excitons in protein molecules was studied in [10]. In our model the excitations of biological media as the whole play the main role in biophotons generation and absorption by the bio-system. We don't considered any model dynamics, however, for such distances it's inevitably should have the solitonic properties [7]. Hence our model supposes that the excitons spread freely over all the volume of bio-system. In that case the exciton exchange can constitute the effective system of signaling and regulation of the bio-system development. The experiments evidence that such long-distance signaling regulates effectively the plant growth, preventing

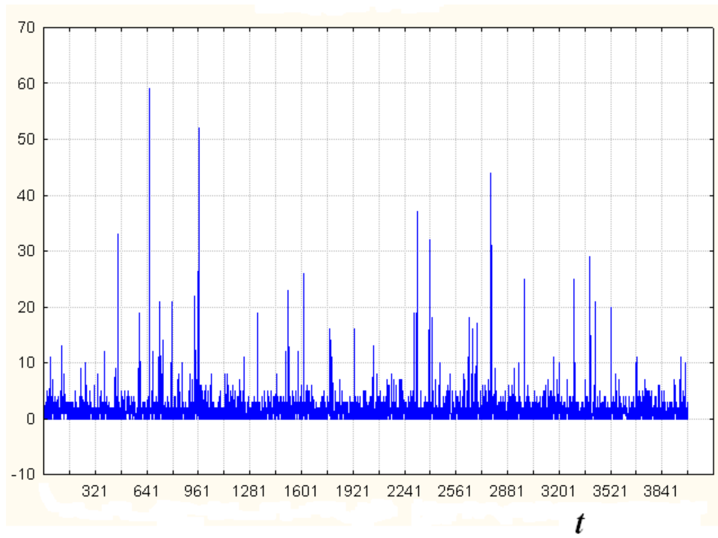

Figure 1: Example of biophoton time spectra for development stage 16, full time scale 400 sec

from the large fluctuations of its global form, i.e. defines their morphogenesis [2, 3].

As was noticed above, BP rate is quite low, about $10\,photons/cm^2sec$ from the surface of large, dense bio-system. If the corresponding field isn't coherent, then it described as the stochastic ensemble of photons. Then at its best the absorption of single photon or narrow bunch of photons can be detected by the bio-system as the single independent 'click' or one bit of information, analogously to standard photodetector devices. This is the photocounting regime of electromagentic field detection well-known in quantum optics [11]. We suppose that the same approach is applicable also for the excitons produced and absorbed in the same bio-system. Under these assumptions, the exciton signaling between two parts of the same bio-system and photon signalling between two distant bio-systems can be quite similar.

It can be expected that the signals which control the cell mitosis and other functions can be similar to the standard discrete (binary) encoded messages transferred between two computers via the noisy communication channels [6]. The origin of such similarity can be understood from the simple reasoning without exploit of information theory machinery. Plainly, for the low exciton or photon radiation rates, typical for bio-systems, the most important problem for the effective signal transfer is to suppress the background. Even for the bio-systems in complete darkness it induced by many sources, like the natural radioactivity, luminescent chemical impurities, etc.. Consequently, as the main criteria characterizing the efficiency of information exchange, the signal to noise ratio K_O can be used, i.e. the ratio of registrated 'clicks' induced by

the bio-system signals and the background. It's natural to suppose that the evolution of living species made the information exchange by means of photon radiation/absorption practically optimal. The average rate of background radiation normally should be constant in time, so for given bio-system with the limited radiation intensity the optimal method to achieve high K_O level is to make the main bulk of the bio-system radiation to be concentrated inside the short time intervals, i.e. the bio-system radiation should be in the form of bursts which would encode the signals transferred to other bio-systems. The experiments with fish eggs, fibroblast cells and other bio-systems demonstrated that the biophotons are radiated by the short-time (less than 1 msec) quasi-periodic bursts [1, 4]; the typical time spectrum for fish eggs radiation is shown on fig. 1.

The influence of biophoton exchange on the organism development was found for many species, in particular their detailed study was performed for the eggs of loach fish ($Misgurnus fossilis$). Note that for the egg colony produced by the fish during its breeding the maximal rate of larvae survival is achieved, if all eggs would develop with the same speed. However, the small variations of temperature and water flow over colony volume and other external factors tend to violate this condition. It seems that the biophoton signaling between distant eggs of the same colony restore their simultaneous development. The results for the optical contacts during 30-50 min between two samples of fish eggs A,B of slightly different age demonstrate the significant synchronization of their development ([1] and refs. therein). However, it was found also that the optical contacts between the fish eggs of significantly different ages result in the serious violations of development in both samples, for fish eggs at early stages the development can simply stop. Those results evidence that the photon signals emitted by fish eggs of different age can have the essentially different structure, which encode the information about their age and corresponding development program.

3 Analysis of Experimental Data

The possible signal structure was exploited for the experimental data on the optical radiation of loach fish eggs. The studied sample is the colony about 200 eggs, which is confined in the quartz container filled with water, their optical and soft UV radiation from the container surface was registrated by the photomultiplier. Its intensity was summed over the nonoverlapping consequent time intervals (bins) with the duration $\Delta = .1$ sec; the experimental run normally consists of $6 * 10^3$ such bins [1]. The measurements were performed for the different development stages, from the earliest ones (cleavage) to the latest 33-35 stages, preceding the free larvae appearance; the average stage duration is about 1.5 hour. The background radiation was measured for the empty container.

Since the background is supposedly stochastic and there is no time correlations between its intensity at different time moments, then the burst periodicity or some other time correlations between them would help to discriminate the

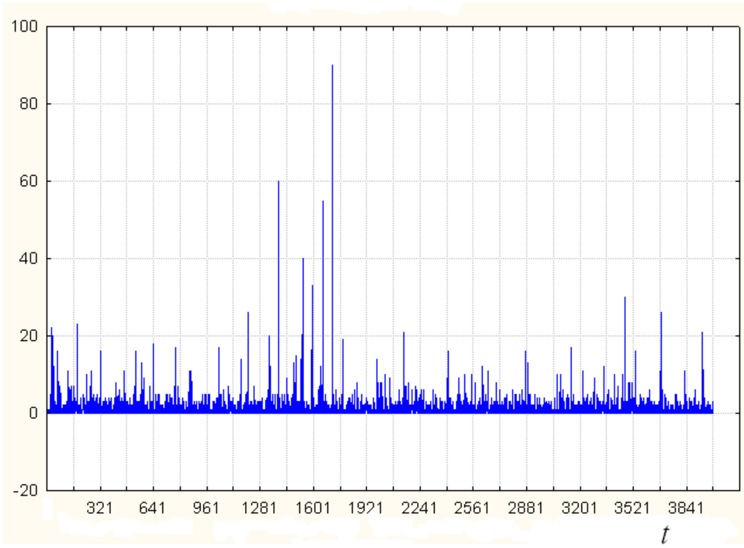

Figure 2: Example of 'message' send by fish eggs at the development stage 32, full time scale 400 sec

background more effectively. Simultaneously, the variations of such correlations can also encode the different signals send by the bio-system. It was supposed that such encoding is performed by the methods and algorithms similar to the standard ones used for noisy communication channels [6]. In this framework, as the model example it can be supposed that the separate message send by the bio-system consists of N bursts of the same height I_r with time interval T_r between them, such messages are divided by the periods of 'silence' T_s when the detectable radiation is similar to the stochastic background, i.e. each message constitutes the burst cluster and such messages divided by T_s intervals are repeated many times [6]. Plainly, for the realistic bio-systems those parameters would have some stochastic spread $\sigma_I, \sigma_T, ...$ around the average values.

First, we studied the discrimination of fish eggs radiation against the background, for which the burst distribution should be random with the arbitrary expectation values of burst amplitude $\bar{I}$ and time interval $\bar{T}$ between the neighbor bursts. The fish eggs radiation is expected to have more periodical structure, for example, if the burst radiation of fish eggs is strictly periodical, i.e. it can be approximated as:

$$A(t) = I_r \delta(t - nT)$$

for arbitrary integer n, then its fourier time spectra is equal to:

$$a_\nu = \int_0^\infty A(\tau) \cos \nu\tau \, d\tau = I_r \delta(\nu - \frac{\pi l}{T}) \quad (1)$$

for integer l and $0 < l \leq \infty$. Thus, the burst periodicity is reflected in fourier

spectra as the sequence of periodical peaks, whereas for background one can expect $\bar{a}_\nu = \bar{I}$, i.e. is constant function with some fluctuations around its average value. Hence Fourier analysis of time spectra can be exploited to discriminate the periodic radiation from the background; STATISTICA-7.0 program packet was used for the data processing.

The preliminary analysis of radiation data has shown that in terms of our model example the typical duration of biophoton 'message' is about 10^2 sec and $\bar{N} = 8.5$, i. e. $\bar{T}$ is about 12 sec, whereas T_s is about $4 * 10^2$ sec. From those estimates it follows that the density of fourier time spectra $f(\nu)$ should be calculated for each consequent set of 1200 bins in given run separately, i.e. 5 spectra for each run. In this template the density $f(\nu) = a_\nu^2 + b_\nu^2$ where b_ν is the value of corresponding fourier integral (1) for $\sin \nu\tau$. Then for each spectra f its autocorrelation:

$$g_l = \frac{\sum\limits_0^M f(i)f(i+l)}{\sum\limits_0^M f^2(i)} \tag{2}$$

was calculated for integer i, l, taking into account the finite length of run and its discreteness $M = \pi\Delta^{-1}$. The sum R of g_l modules over such set is used as the selection criteria:

$$R = \sum_0^M |g_l|$$

It was found that for arbitrary R threshold which selects about 80% of fish eggs runs, only $16 \pm 4\%$ backgorund runs are selected for $12-16$ stages ($10 \div 15$ hours after fertilization) and $23 \pm 6\%$ for $30 \div 34$ stages. It evidences that the fish eggs radiation has more periodical structure than the stochastic background, the possible candidate for such periodical signal (message) is shown on fig. 2. After such selection it was found that the individual messages have the length about $.6 \div 1.5 * 10^2$ sec and they are interspersed by the periods of silence about $3 \div 6 * 10^2$ sec. Each message consists of $6 - 14$ distinct high bursts, despite significant fluctuations, their amplitudes I demonstrate gaussian-like dependence on the time distance from the message centre (see fig. 2). In each individual message the time intervals T between the neighbor bursts with I higher than some threshold I_0 are nearly the same with some dispersion or differ by the whole number, i.e. are equal to $2T, 3T$, etc.. Yet T average value can differ from one message to another significantly, about factor 1.6.

Concerning the dependence of signal form on development stage, our analysis indicates that the most pronounced change suffers $\bar{T}$ value. To demonstrate it, the inclusive (i. e. over all run) T distributions for the bursts with I higher than $I_0 = 15$ units (see fig. 1) were obtained for several development stages. To enlarge statistics, we summed in the same plot the data for $8-11$, $12-16$ (fig. 3) and $30-34$ stages (fig. 4). Under these conditions the total exposition time for each plot was 130 min.. For each distribution the systematic errors are negligible, the statistical errors for each experimental point are equal to $N_{events}^{\frac{1}{2}}$,

where N_{events} is the abcyssa value in this point. The obtained $\bar{T}$ expectation values are equal to $\bar{T} = 11.2 \pm .3$, $\bar{T} = 9.2 \pm .3$ and $7.1 \pm .2$, sec for $8 \div 11$, $12 \div 16$ and $30 \div 34$ stages correspondingly. Meanwhile, the average number of bursts is nearly the same for all three cases, whereas the average burst amplitude $\bar{I}$ for $30 - 34$ stages is about $15 - 20\%$ larger than for $8 - 11$ stages, yet the overlap of their I distributions is essentially larger than for T distributions.

The essential feature of all three plots is the presence of several large peaks, which are effectively higher than the possible statistical error limits. Their parameters need further analysis, but it's worth to notice that for $8 - 11$ and $12 - 16$ stages two most prominent peaks seems to be generically connected, shifting from 5 to 6 sec and from 10.3 to 10.8 sec. Note also that T maxima positions of three largest peaks for $8 - 11$ stages are related approximately as $1 : 2 : 4$.

The obtained distinctions explain, probably, how the radiation from fish eggs of different age can influence the 'detector' samples in a different way. Despite that the difference of signal parameters is only statistical, the multiple repetition of such messages can be eventually percepted by the 'detector' fish eggs as the different instructions which would be fulfilled during their subsequent development. It seems that the most important for their encoding is T difference, because the burst amplitude produce mainly the threshold effect, i.e. only the condition like $I > I_0$ is accounted for some arbitrary I_0 which is proper for given bio-system. If those conclusions will be confirmed by further experiments, it would mean that the main encoding algorithm for fish eggs radiation has the analogue realization, despite the produced signal is constituted by the sequence of discrete bursts. Such information encoding is similar to the digital-time analogue (DTA) algorithm used in some electronic systems. Note that the similar encoding of electric pulses supposedly is exploited in the brain neuron chains [8].

Our model assumes that the bio-system's field is noncoherent, yet it's worth to consider also the possibility that this e-m field of bio-system can possess the spacious short-time coherence within the observed photon bursts, similarly to the coherence of laser pulse. Some experiments evidence that such biophoton coherence really takes place [12]; in this experimental set-up the transparent quartz plate was installed between the inductor and detector bio-systems. In the first run the plate parallel surfaces were smooth and polished, so that it doesn't perturb the phase relations between the different pieces of wave front of incoming photons. In another run, the plate has the random deflections from the surface parallelism, which violated such phase relations, and so resuly in the violation of the impact wave coherence. It was found that in comparison with the control sample of isolated bio-system, the radiation passed through the random surface results in the gain of mitosis rate of 20%, yet for smooth surface it reach the rate of 45%. In our framework, it's reasonable to suppose that the field with such 'transversal' coherence more effectively produce the collective excitations in the cells cluster, than noncoherent field. If this hypothesis is correct, then such coherence effects will not change the principal scheme of communications proposed here, rather, it would enlarge its efficiency.

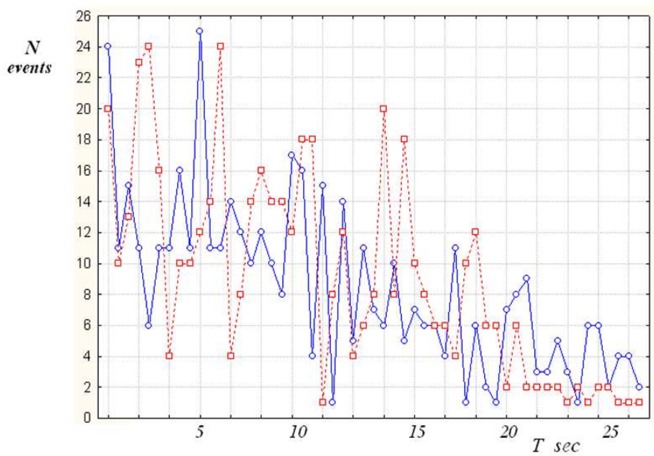

Figure 3: T distribution for fish eggs radiation; solid line: $8 \div 11$ stages; broken line $12 \div 16$ stages

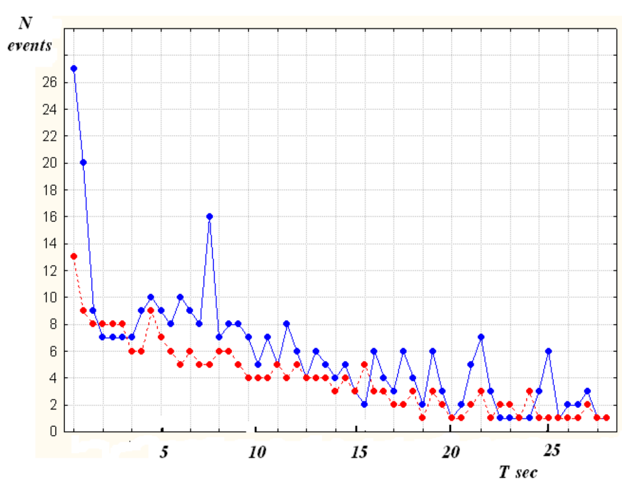

Figure 4: T distribution for fish eggs radiation; solid line: $30 \div 34$ stages; broken line - background

For the conclusion the obtained results can help to reveal the mechanism of communications between the distant samples of fish eggs and permit to describe the universal features of biophoton signaling between the separate bio-systems. The similar mechanism can, on the all appearances, describe the exciton signaling inside the dense bio-system. The cell signaling and regulation features are well studied for the extracellular biochemical reactions [8]. Concerning the chemical signaling in the tissues, its efficiency and precision is principally restricted by the molecular diffusion effects inside the bio-system media and so can transfer the signals only for small distances. Note also that the exciton signaling inside organism can be much faster, than the chemical one by means of molecular messangers. Hence it can be efficient in case of stress or the abrupt change of external conditions. Experimental results show that under the different stress conditions the photon rates from bio-system can rise in short time significantly, probably, as the consequence of intensive internal signaling [2, 3].

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